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MEETING PAPER

SURFACE FEATURES INDICATIVE OF SUBSURFACE EVAPORITE DISSOLUTION: IMPLICATIONS FOR STORAGE AND MINING

by

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ABSTRACT

Evaporite deposits comprise a substantial portion of the earth's near-surface rocks and are appropriate targets for exploiting storage of liquid and gaseous hydrocarbons, and for extractive mining. They also provide ubiquitous opportunities for dissolution by groundwater; consequently, the surface expression of these processes is widespread. Surface features commonly occur from entirely natural processes, and they are sometimes induced as a result of human activities. Because these processes create subsidence-related depressions, sinkholes, cracks, and other undesirable effects, their etiology becomes important. Therefore, recognizing, understanding, predicting, and mapping these features is crucial to the safety of operations. For these reasons, dissolution features should be a major element in site characterization studies of evaporites.

Bedded and domal salt deposits each show different kinds of surface features resulting from subsurface dissolution, although many are alike. The essential verticality of most features in domal salt combined with limited area1 extent is the main difference from features in bedded salt. Similarities with dissolution features over carbonate terrain also exist, producing "salt karst" that has been confused sometimes with limestone karst. A major distinction affecting the two rock types is that groundwater will invade carbonate masses through joints and fractures, whereas salt dissolution most often proceeds from the edges of the body. Accordingly, peripheral portions of salt masses require more complete characterization, especially regarding salt properties and the groundwater regime, and thus the potential rate of dissolution.

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Introduction

Salt dissolution is the common thread that brings us together as the Solution Mining Research Institute (SMRI), but our principal aim is in controlled dissolution. Subsurface dissolution which produces unplanned surface effects in the form of subsidence, and most noticeably, collapse features, is generally undesirable. And so our goal then should be to recognize what we can influence, but also can avoid or minimize through prudent engineering, and to distinguish that over which we have no control.

The phenomenology of subsidence and sinkhole formation have been topics on the technical program at virtually every SMRI meeting in the last 30 years, and the subject of no less than 20 SMRI research projects, covering many different evaporite environments. Long-term subsidence resulting from salt creep closure is usually less conspicuous and dramatic than solution-induced subsidence and consequently is given lesser treatment here. Oil and gas operations also produce subsidence and solution-induced collapse features where evaporites are present, but they are not addressed in this paper. However, where nearby storage or mining operations exist, that aspect also must be evaluated.

Evaporite minerals that undergo dissolution and which are of most concern are halite, sylvite, and camallite, and to a lesser extent gypsum and anhydrite. There are significant differences in solubility; gypsum is about 150 times less soluble than halite, and limestone is 7000-8000 times less soluble than halite. Evaporite karst topography is similar to limestone karst in many respects, but there are also significant geological distinctions. Evaporite karst has been studied much less than limestone karst until fairly recently, and was only termed "karst" about 1960 [Korotkevich, 1961]. The recent increased interest results from the incentives provided by several types of storage activities.

The recent bibliography compiled by the Diamonds [1993] lists 23 entries under "sinkholes" and 64 entries under "subsidence." The events that we consider here today have for the most part been described previously; however, the surface effects of subsurface dissolution continue as we speak, however slowly the rate may be. Consequently, I believe we must exercise continuing vigilance; but more significantly, specific steps in our engineering pre-planning and site characterization efforts are needed. This should lead to fewer unanticipated events in the future. Those readers requiring more geological detail are referred to the reference listing.

Man-Tnduced Features Over Storage and Mining Operations

Dissolution features which develop at the surface above engineered storage caverns are attention getters, as we know all too well. Both domal and bedded salt deposits are affected, but in rather different ways. More induced features may be witnessed over domal salt than bedded salt perhaps, because there is more storage and mining associated with it. And it appears there are more natural subsidence features associated with bedded deposits, principally because the area1 extent is vastly greater. A few examples from recent history remind us of the problems that man has created -- inadvertently:

BOLING DOME, TX, was the site of an unexpected sinkhole formation in 1983, that closed highway FM 442 for some time therafter. The cause of this was speculative at first, but Thorns' [1990] SMRI paper provided clear evidence that earlier sulfur mining was responsible for producing dissolution voids in the caprock. Whether salt dissolution below the caprock is involved is unclear, but it is evident that more complete documentation of mining history will be essential.

Cavern Lake (formerly Cavern 7) at **BAYOU CHOCTAW DOME, LA, dome** was the subject of a paper at last fall's SMRI meeting. This man-induced sinkhole formed in 1954 over a period of several days **(Figure 1).** This occurred prior to the advent of modern leaching methods and sonar surveying. A recurrence of such an event seems unlikely now, unless safe buffer distances are somehow ignored, or human error prevails. Cavern 4, having similar geology, also experienced uncontrolled leaching into caprock; it now appears to be stable, but is being monitored periodically [Neal et al., 1993]. Similar incidents of apparent uncontrolled brining led to major sinkhole formation at **BLUE RIDGE DOME** near Houston in 1949, and at **GRAND SALINE DOME, TX,** in 1976. Lack of adequate salt roof was the likely cause of both of these incidents [Coates et al., 1981].

JEFFERSON ISLAND DOME, LA, attracted national news in November 1980 because of the sudden, spectacular drainage of Lake Peigneur into the mine below. Fortunately, no lives were lost but significant land use disruption occurred locally and a salt mine was closed forever, causing economic hardship and employment interruption to the mine workers. While perhaps the most dramatic of recent subsurface dissolution effects, it exemplifies the speed at which leak problems can run away from us. This event can be attributed to human error and possibly inaccurate mapping. Autin [1994] has commented on this incident as a graphic portrayal of conflict in resource utilization leading to incredibly massive human involvement with little gain for mankind. Although the mine is closed, a gas storage project is currently planned [Thorns, 1994].

The 1994 flooding in the **RETSOF MINE,** NY, occurred in'bedded Salina salt and bears little resemblance to Jefferson Island. The formation of surface effects, including cracks and subsidence sinks, occurred subsequent to massive water influx following a Magnitude -3.5 seismic event on March 12, 1994 [Thompson, S. N., 1994].

The Cargill collapse sinkhole at **HUTCHINSON, KS,** formed over a period of three days in late October 1974, leaving a circular depression some 300 feet in diameter and nearly 40 feet deep. Post-event drilling and study of this feature (as part of a SMRI research project) revealed a gallery roof in the bedded salts spanning more than 400 feet. Eventually the strength of the roof rock was exceeded and failed. Earlier uncontrolled brining by the former Barton Salt Company over a period of some 86 years contributed to this unexpected event. The post-mortem analysis showed that several warning signs, e. g., subsidence, had been noted, but not acted on [Walters, 1977]. Other sinkholes over mines had occurred in the Hutchinson salt previously, so it was not a total surprise.

At **WEEKS ISLAND, LA,** a sinkhole was first noted in May 1992 along the south-central portion of the island, directly over a trough that occurs in the top-of-salt **(Figure 2),** and the edge of the SPR mine. The size or volume of this feature was sufficiently large (estimated 650 yd^3) that the possible correlation of its occurrence over the salt trough, or its association with an anomalous zone [Neal et al., 1993] is being investigated.

Subsurface exploratory drilling around the DOE Service and Production Shafts in 1986 identified the presence of irregularities and saturated void spaces along the top of salt. Such features, if present under the sink hole, could possibly account for collapse of the surface into such voids. This type of process effectively describes "salt karst" development, although the term karst typically is used in limestone terrain. Highly irregular salt topography has been reported on other domes, sometimes in association with structural features of the dome. More widespread salt karst is seen over the Supai salt basin south of Holbrook, AZ, and in other locations, but these are bedded salt deposits with entirely different groundwater regimes.

An alternate explanation is that water has been leaking into the mine and dissolving salt in the process, which in turn creates void space into which overlying sediment can slump. Thorns [1994] noted that Kupfer's 1977 mapping in that part of the mine (prior to oil emplacement) showed black salt adject to the present sinkhole area; black salt is sometimes associated with anomalous zones. Further study is currently underway at Weeks Island, including seismic reflection, crosswell seismic tomography, core drilling, and near-surface gas mapping. However, until more data becomes available, the cause of this feature will remain speculative.

Unanticipated events such as these are usually explainable in ***hindsight.*** Our goal in planning storage and mining projects should be to understand their causes sufficiently well so as to avoid them in the future. Thus, the purpose of geological site characterization is to anticipate where such dissolution and subsidence events are possible, and to make appropriate precautionary caveats in siting facilities.

Natural Features Caused by Subsurface Dissolution

The previous examples, except the Hutchinson, KS, sinkhole, occurred in domal salt, all of which commonly display differential movement along individual segments or “spines” within the salt mass. The boundaries between spines are often manifested in anomalous zones (Azs) that typically have surface expression, including features indicative of dissolution [Kupfer, 1988, 1989, 1990; Autin et al., 1986; Thorns et al., 1992; Neal et al., 1993]. These anomalous zones have been observed best in underground mines, but have also been mapped at other domes using well logs [Magorian et al., 1988]. Recognition of AZs is difficult, but the identification of linear surface depressions, ponds, etc., should cause one to *suspect* them [Magorian, 1993]. Autin [1994] notes surface slope changes in combination with other evidence help to substantiate the presence of Azs. Some surface features similar to those previously noted occur in bedded salt, but many are attributed to entirely natural causes. While many irregularities and discontinuities are noted in bedded salt deposits, the term anomalous zones does not apply, as it was proposed only for domal salt.

The occurence of evaporite dissolution proceeds from the outer boundary of salt masses, almost without exception. Where unsaturated (with respect to NaCl) groundwater moves downdip via Darcian flow through conductive strata and encounters evaporites, the surface topography above will reflect some aspect of dissolution in the form of subsidence or collapse. Virtually every geologic deposit of evaporites at shallow to intermediate depth will contain some indication of dissolution. Five examples from bedded evaporites in Kansas, Texas, New Mexico, and Arizona follow; surface aridity is not an impediment to the formation of evaporite karst, as long as there is sufficient groundwater flow.

Surface features in evaporites parallel those in limestone and dolomite: depressions, sinkholes, swales, breccia chimneys, subsidence valleys, and other features having both negative and positive relief have been noted.

High Plains Subsidence and Plava Lake Basins

SEVENMILE BASIN, a large ephemeral lake (playa) in the Texas panhandle, formed because of subsidence. Shallow seismic data show reflectors indicating that dissolution of at least 350 ft of Permian evaporites has occurred and is responsible for the subsidence [Paine, 1994]. Many other basins show similar evidence; Gustavson et al. [1980] showed that as much as 1000 A had been removed form other areas of the Southern High Plains. Nearly 30,000 playas, depressions, and subsidence basins exist on the high plains and all are underlain by Permian evaporites. It seems likely that solution-induced subsidence is involved to some extent in most of them.

Other major playa basins, such as the -500 mi2 ESTANCIA **BASIN, NM,** (Figure **3),** have relatively thin fill as compared with other basins and show a considerable amount of Miocene-Pleistocene erosion and solution subsidence [Hawley and

Love, 19913. The evaporite sequence contains gypsum rather than halite.

Salt Karst Features in the Permian Supai Formation. Arizona

The **HOLBROOK BASIN, AZ,** is underlain by bedded Supai salt, some 2300 mi2 in extent. The southern margin is being dissolved by the encroachment of northward-flowing groundwater from the Mogollon Slope, producing a major subsidence and collapse zone. More than 300 sinkholes, fissures, and possible breccia chimneys occur adjacent to this zone **(Figure** 4). There is also a major series of depressions and a playa lake basin called Dry Lake Valley, covering some 120 mi2. This zone of salt removal has produced a major gravity depression, coincident in general with the surface topographic depression. Peirce [1981] suspected that the regionally extensive development of these internally drained depressions occured where salt is within about 1000 ft of the surface. The main salt mass ranges up to about 500 ft thick, with some areas of sylvite concentrations along the northern portions. This may be the largest solution collapse feature in the world according to Peirce [1994]. The so-called Holbrook Anticline, in all likelihood, is a structural flexure caused by solution-induced subsidence **(Figure** 5). This occurrence is of more than just academic interest; 11 storage caverns exist in the northern portion of the salt body at Adamana, AZ., on the side of the salt mass opposite from the dissolution front.

Bahr [1962] noted that some deep sinks seen on 1953 air photos were absent on photos taken in 1936; thus, he thought that dissolution and collapse was ongoing, but the overall rate of advancement of this dissolution front has not been determined. Field inspection of some of these sinks and fissures in early 1994 by the author showed recent activity, whereas many others are conspicuously eroded and obviously older. This range in characteristics and recency of activity suggest that some newer remote sensing formats may be useful, e. g., thermal infrared imagery (TIR). A wide range of sinkhole diameters and depths were noted, from very small and shallow, up to 600 and 150 feet, respectively **(Figure 6).** Some sinks coalesced in arcuate form, possibly suggesting circulating subsurface groundwater. A common valley containing many recent collapse features was also observed, together resembling a chaotic jumble. Some collapse sinks appeared to be forming along active fissures that were propagating parallel to the dissolution front and the trend of the "Holbrook Anticline." Recent reports of the shallow playa lake in Dry Lake Valley draining several hundred acre-feet of water overnight also substantiate the notion of active fissure formation [Wellendorf, 1994].

Solution Features in the Hutchinson. Kansas. Salt

The **HUTCHINSON SALT** member of the Permian Wellington Formation is up to 555 A thick and underlays much of central and south-central Kansas. Dipping slightly westward, a dissolution front occurs on the updip eastern edge where groundwater is actively removing salt. It is along here that the erratic "Wellington Lost Circulation" zone occurs, a very well known feature to oil well drillers. This zone extends for more than 100 miles. Surface subsidence and collapse have led to the development of sinks and valleys. Geologic investigations led Fent [in Walters, 1977] to conclude the rate of migration of this dissolution front is 2 mi per million years since the late Pleistocene, somewhat less than in earlier Pleistocene. This updip area is the only known occurrence of dissolution within the salt mass, prior to man's drilling and mining activities during the past 70 and 100 years, respectively. Walters [1977] believes no solutioning from the top downward has been detected.

The Meade Salt Well is a natural sinkhole in Meade County, Kansas, that formed suddenly in 1879 in an area that contains numerous hollows and sinks, some of which can be attributed to solution collapse into cavities in the underlying Permian salt beds. Some evaporites younger than the Permian salt may be involved here. Geological study some 60 years after the collapse showed that faults updip from the sinkhole transmit fresh groundwater under hydrostatic pressure and dissolve openings in the underlying salt beds [Frye and Schoff, 1942]. Evidence for the dissolution is seen at lower altitudes to the east where salt springs emerge.

Salt Karst Features in the Delaware Basin, New Mexico and Texas

The **DELAWARE BASIN** in Southeastern New Mexico and West Texas is largely contained within the Capitan Reef structure, an elongate limestone formation perhaps best known for the Carlsbad Caverns along the northwest margin. The Capitan limestone is noted for its porosity and fracture systems which readily transmit ground water; where overlain by evaporites it provides conduits for dissolution to progress, and numerous swales, sinks, breccia chimneys, and other subsidence-related features have been associated with it. The Delaware Basin is one of the most intensively studied evaporite basins in the world, having been the site of the Gnome nuclear test in 1962 and now the Waste Isolation Pilot Plant (WIPP). Thus a strong interest in salt karst features and other aspects of dissolution has existed for more than 30 years, especially with regard to process rates and locations Vine, 1963; Lambert, 1983]. Representative features are discussed in the following paragraphs.

The eastward dip of the sediments in the Basin cause groundwater to flow eastward and salt may have been removed as the dissolution front moved eastward. Bachman and Johnson estimated the horizontal migration rate of the dissolution front was about 6 to 8 miles per million years. The current area of salt removal (or possibly non-deposition, according to some authors) is shown at **Figure** 7. The current Pecos River has migrated geologically ; its earlier position was responsible for effecting substantial dissolution, as shown on Fig. 7.

San Simon Swale is a 100 mi ^{2} depression located at the eastern margin of the Basin, over the Capitan Reef It has formed as a result of evaporite removal by dissolution of evaporites in the underlying Rustler and Salado formations. San Simon Sink is the lowest point in the depression, some 100 ft deep and 1/2 mi^2. It contains a secondary collapse sink several hundred feet across and 25-30 ft deep, that subsided abruuptly in 1927. Annular rings that cut the surface around the sink suggest continuing subsidence and readjustment to the earlier collapse. The position of the sink over the reef led to the suggestion by Lambert [1983] and many other authors that the collapse originated in a groundwater cavity in the Capitan Reef and that the sink may be a modern analog of a breccia pipe.

Wink Sink in Winkler County, TX, formed suddenly on June 3, 1980 and within a day had spread to its maximum width of 360 A and depth of 110 ft. Johnson [1986; 1993] believes the original cavity beneath the sink occurred as a result of dissolution in the Permian Salado Formation, at a depth of some 1300 ft. This feature is also over the Capitan Reef, and is undoubtedly associated with that formation, similar to the San Simon Sink. Johnson points to the abrupt and unnatural thinning of the salt units in the vicinity, combined with the concurrent thickening of overlyoing units as proof of the natural dissolution. However, he also believes that nearby oilfield injection activities contributed to this particular event. Injection activities elsewhere have produced similar features.

“Breccia chimneys” are features of positive relief, originating by the gravity collapse of flanking materials into sinkholes and forming “chimneys” in the throat leading to the void below. Subsequent erosion and subsidence of the surrounding more soluble country rock leads to such features. While not nearly as common as sinkholes and other collapse features, breccia chimneys may be locally significant, such as on the northern border of the Capitan Reef (Figure 7). “Karst domes” may resemble breccia chimneys as features of positive relief, but their cores contain older, as well as younger, rocks than their flanks.

Nash Draw is a southwesterly trending depression some 16 mi long and 3-9 mi wide, with its sump in Salt Lake at the southern end. The underlying Rustler Formation has undergone dissolution of gypsum; more than 100 caves, sinks, fractures, swallow holes, and tunnels exist in a complex karst topography, apparently still active today [Bachman, 1981]. An extensive drilling program conducted for WIPP showed that dissolution of halite in the Rustler and upper Salado formations is responsible for the subsidence and overall formation of Nash Draw [Lambert, 1983].

Solution subsidence structures are well known in the Devonian Prairie Formation of southern Saskatchewan. The **Rosetown Low** and the **Regina Hummingbird Trough** show formation thinning of several hundred feet, which has been attributed to interstratal dissolution of evaporites at depth. [DeMille et al., 1964]. Underlying reefs and bedrock fractures very possibly suupply the necessary circulation channels for additional localized evaporite dissolution, similar perhaps to the Capitan Reef features. Surface expression of this dissolution is obscured by the presence of glacial drift.

SUMMARY AND CONCLUSIONS

Subsidence and collapse features are usually the principal surface evidence for evaporite dissolution at depth, as no other direct evidence may exist. This observation may be intuitively obvious to most of us, but also may be equivocable during litigation. Subsidence in the form of local subsidence features, including sinkholes, fissures, swallow holes, and breccia pipes, are present almost everywhere that salt or gypsum are exposed to circulating groundwater. The examples used here are but a small sampling of the seemingly unlimited population of salt features, but they also demonstrate the rich variety of effects.

"Karst topography" terminology applies generally to salt as well as to limestone; the term was first used regarding salt only about 30 years ago, but its acceptance is now widespread and embraces a large variety of features. A major difference between salt and limestone is that the former is some 7000-8000 times more soluble. Even gypsum is some 150 times less soluble than salt [Fairbridge, 1978]. However, salt is usually impervious to solutioning and can only be attacked on external surfaces, whereas limestone contains faults, fractures, joints and multiple internal surfaces. Caves persist in limestone but cannot last for long in salt. Although there are major similarities, it would be misleading to imply karst is the same everywhere. There are local distinctions in almost every locale that karst features occur, because of the site specific nature of the materials involved, the hydrologic regime, overburden, and climatic factors.

A variety of surface features are seen that indicate subsurface dissolution of evaporites is ongoing, both in domal salt and especially in bedded deposits. With regard to the latter, subsidence of regional dimensions is common but often is recognizable only by detailed study of well logs. Swales, valleys, draws, and playa basins are all effects of evaporite removal by dissolution, but these features may also be produced by quite dissimilar processes. Collapse features, fissures, grabens, and subsidence basins vary widely in appearance, depending in large part on the overburden material, and the nature of the subsurface voids. Collapse features in evaporites are generally associated with dissolution voids at shallow depths; deeper evaporites are susceptible to creep and / or stratabound dissolution and more apt to manifest as subsidence features of broad dimensions.

Precision measurement of subsidence that is produced by salt creep closure following either conventional or solution mining is recommended as a matter of course – wherever subsurface voids are created. It may be the only means of detecting when anomalous events and processes occur, and it may be the best form of self-protection if potential liability exists. This message has been made clear in the SMRI literature.

Wherever there is subsurface salt exposed to undersaturated groundwater, it is axiomatic that there is ongoing dissolution. **Thus, the principal objective of geological site characterization must be to specify rates**

of removal, and where surface effects might occur. Even though dissolution rates can sometimes be specified only to accuracies of "miles per million years," these are beneficial if averaged over extended geologic time. Because many areas reveal quite recent activity, time sequence aerial photography can be particularly beneficial. Aerial photography taken in the 1930's is often of sufficient quality to serve as **a** "baseline" for 60 yr comparisons with more recent remote sensing imagery. High quality, large-scale color photography is one of the best ways to observe dissolution features. Thermal infrared imagery (TIR) may be useful in certain applications, especially where moisture variations occur around features.

Even though geologic site characterization precedes the initiation of most projects, *it must not be thought of as a one time effort.* That is because geologic concepts involving salt domes are evolving continuously, and also because most all storage and mining are also changing – usually because of the natural development of projects. This implies that **things do change, and that unanticipated events can happen.** Updates to most projects should be accomplished at least every 10 years; this is now required by law for U. S. Department of Energy projects.

Finally, **evaporite dissolution is a subject of considerable geologic complexity,** and one that requires substantial study effort to reach reasonable certainty with respect to the safety of storage and mining projects. However, to not put forth the necessary effort could very easily be an invitation for serious and costly problems to occur.

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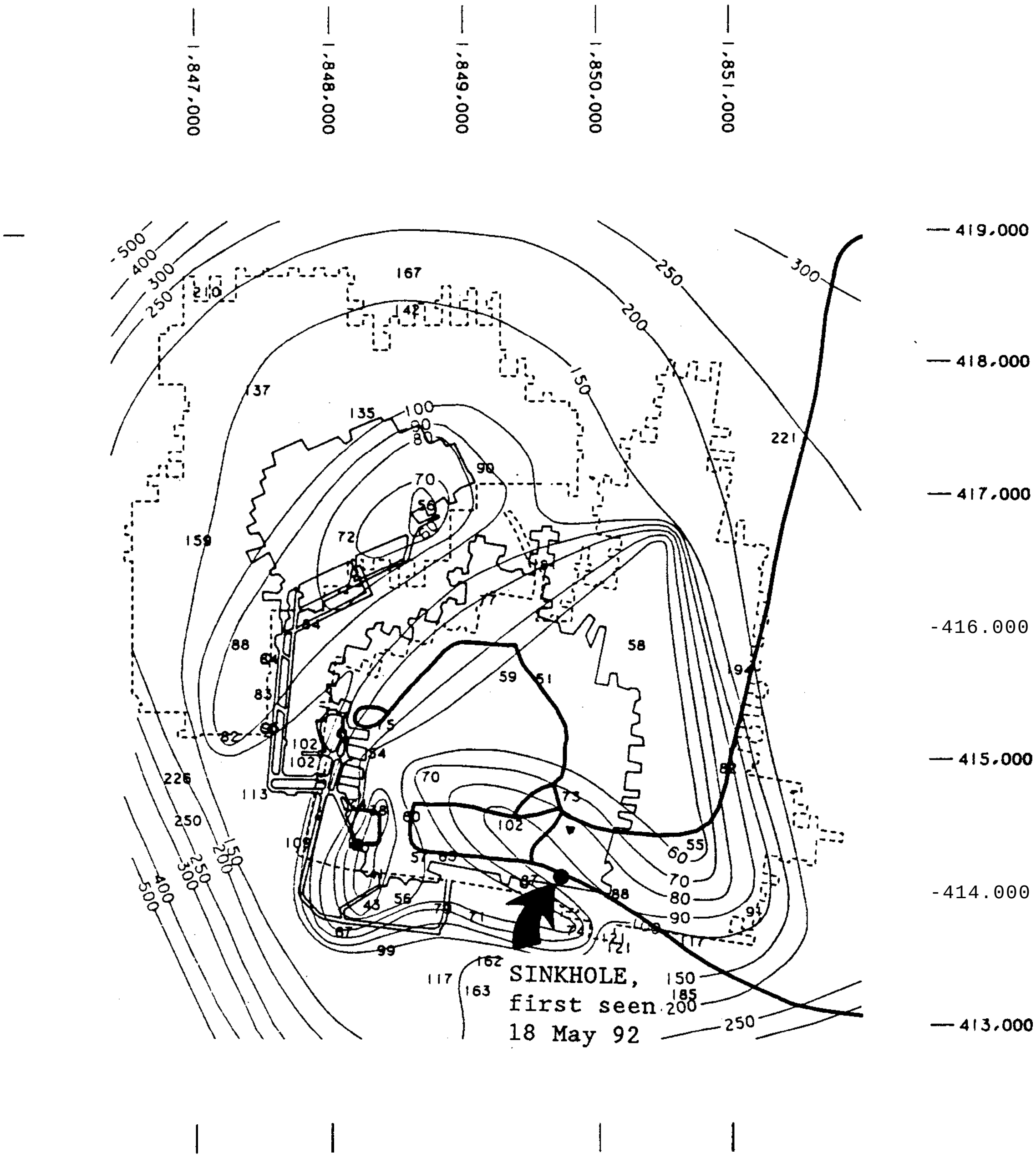
FIGURE 1 Aerial view of Bayou Choctaw salt dome, showing Cavern Lake at left and Cavern 4 at center (arrow) of photo.



LEGEND:

226 ELEVATION OF TOP OF SALT IN FEET BELOW MEAN SEA LEVEL AS DETERMINED FROM WELL LOG

200 TOP OF SALT CONTOUR IN FEET BELOW MEAN SEA LEVEL

LIMITS OF MINE WORKING

NOTES:

1. CONTOURS ARE INTERPRETED FROM GEOPHYSICAL WELL LOG DATA AND GEOLOGIC ASSESSMENT.

BORING LOCATIONS AND DEPTHS HAVE BEEN DETERMINED BY OTHERS. ACRES INTERNATIONAL CORPORATION IS NOT RESPONSIBLE FOR THE ACCURACY OR COMPLETENESS OF THESE DATA.

SCALE 0 1000 2000 FEET

ACRES | SANDIA NATIONAL LABORATORIES

WEEKS ISLAND SPR SITE

DETAIL OF SALT CONTOURS OVER MINES

ACRES INTERNATIONAL CORPORATION
T. R. MAGORIAN

Figure 2

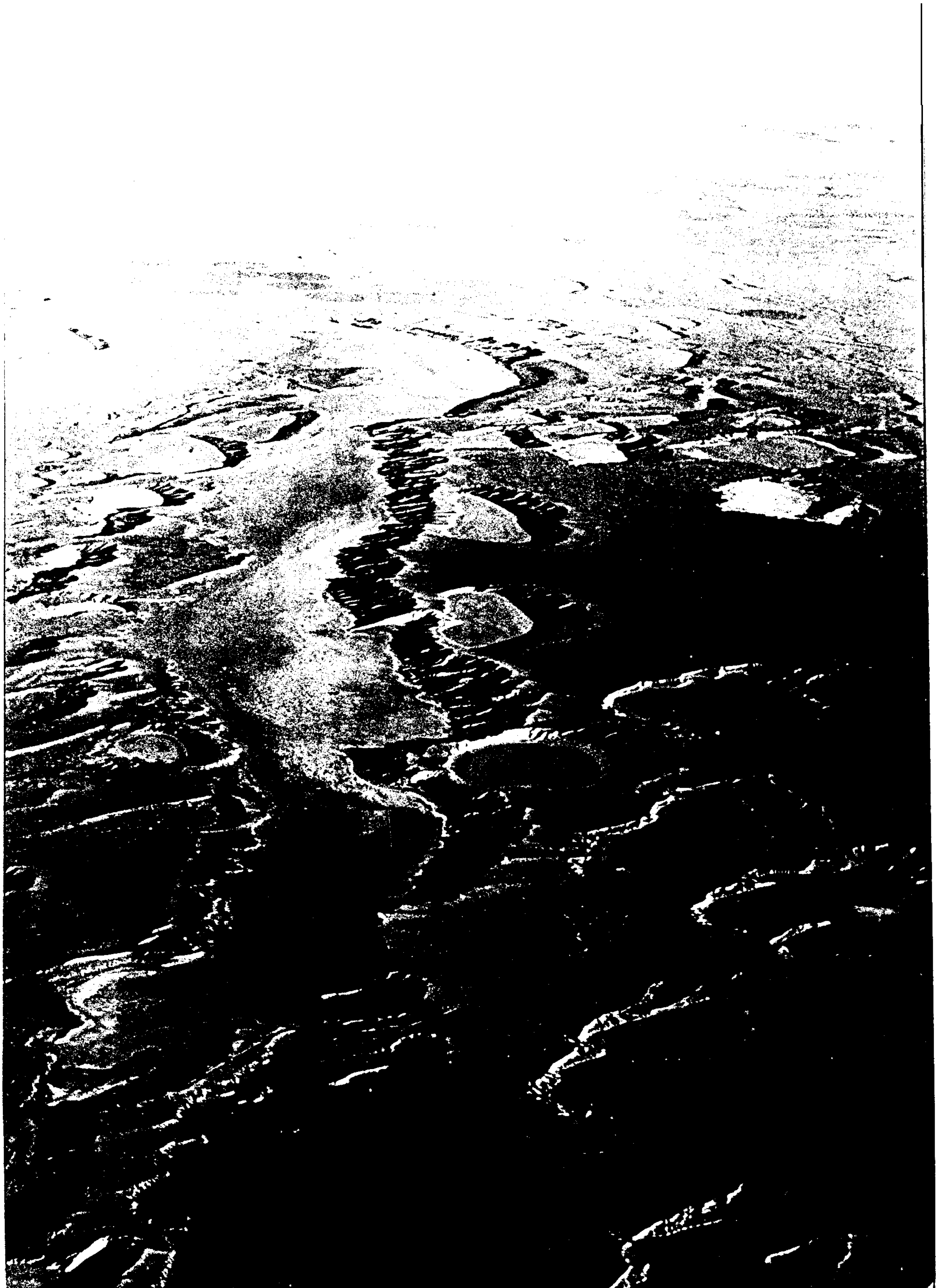


FIGURE 3 Estancia Basin, New Mexico, covering some 500 mi^2 and containing more than 100 individual playa lakes, owes its origin to deep-seated dissolution of gypsum and concomitant subsidence. The basin contained a large, ~100 ft deep Pleistocene lake; it now contains only shallow ephemeral lakes.

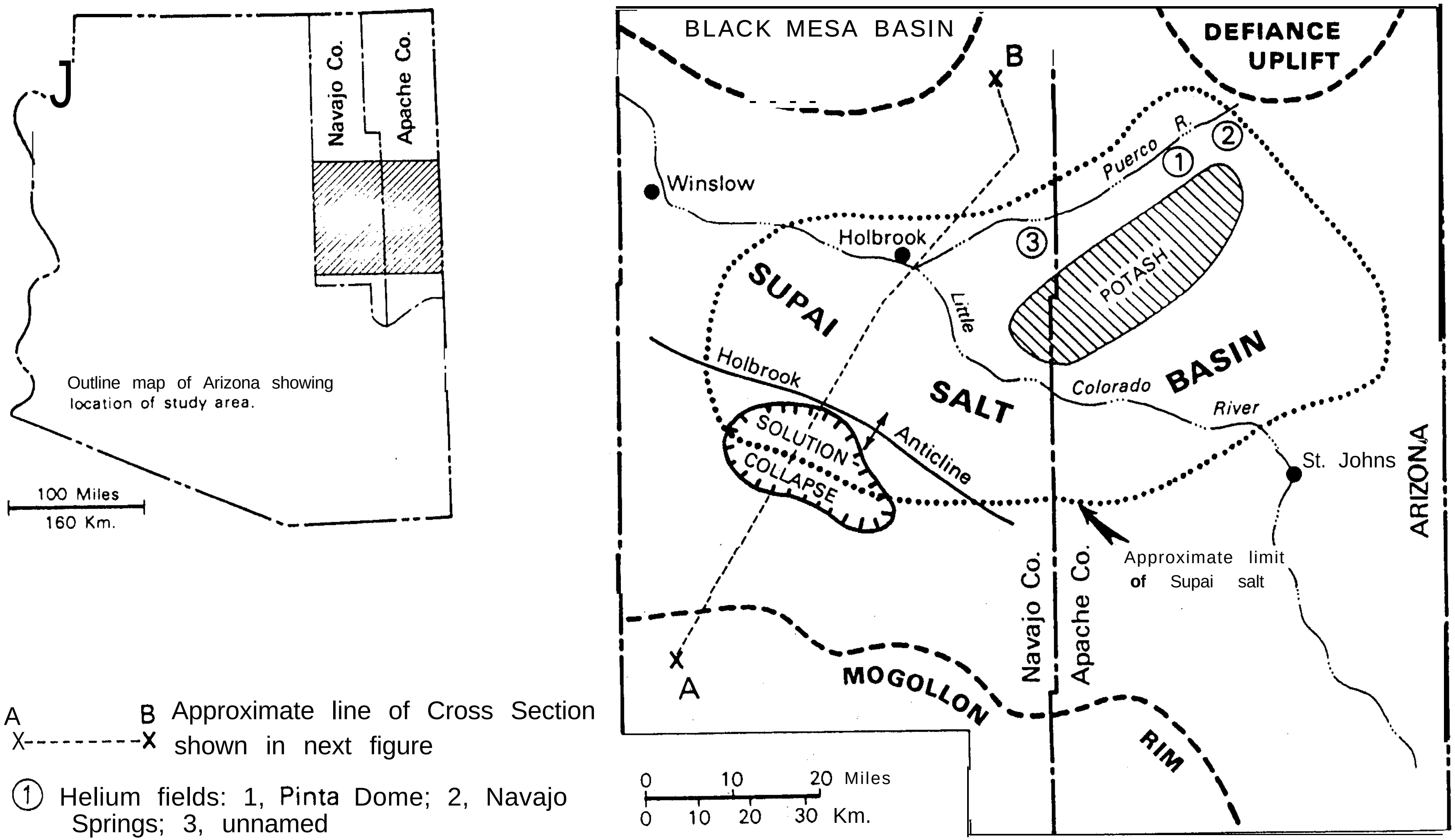


Figure 4 Map of Supai salt distribution within the Holbrook, AZ, Basin. Major solution collapse area occurs at southern edge of salt, adjacent to the Holbrook Anticline, possibly a structural flexure created by salt dissolution. Hundreds of sinkholes, fissures, and collapse structures occur.

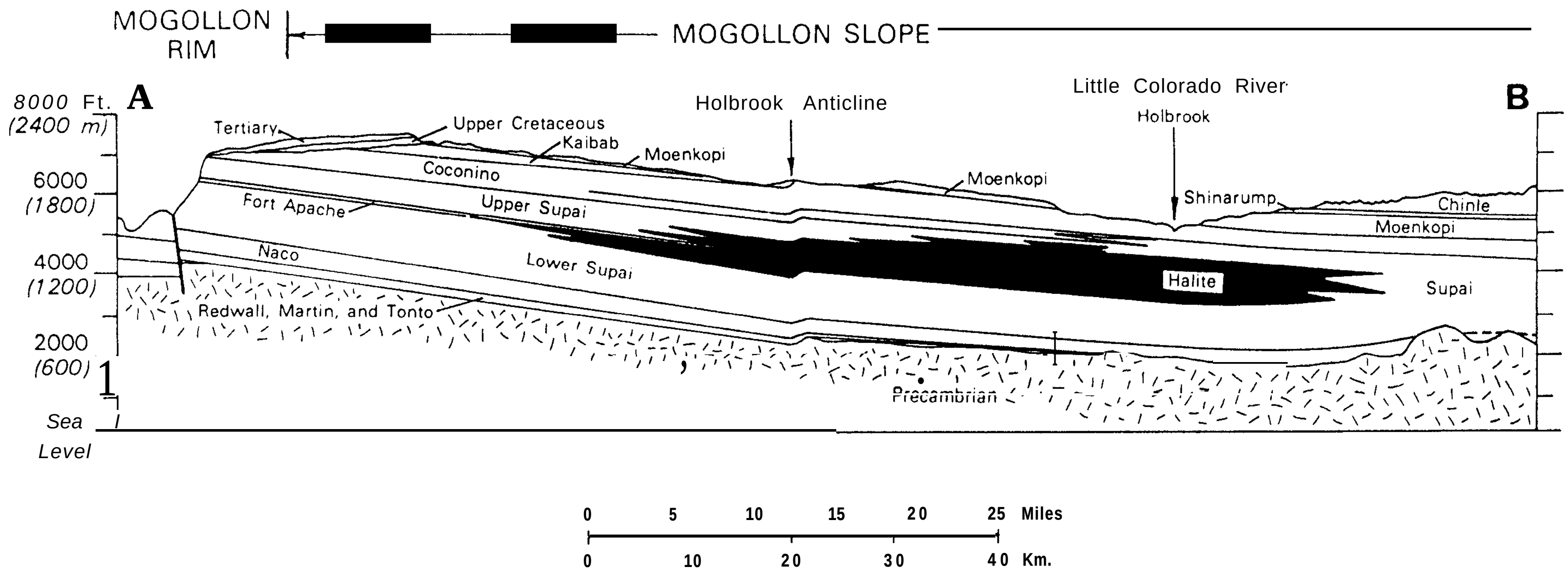


Figure 5 Cross section through the Holbrook, AZ, Basin showing the northward dip of the Upper Supai halite body, from the Mogollon Rim to the Little Colorado River. The so called Holbrook Anticline may be a structural flexure created along the nortward moving dissolution front. Major dissolution features, including more than 300 sinkholes, fissures, and collapse structures occur along this front,

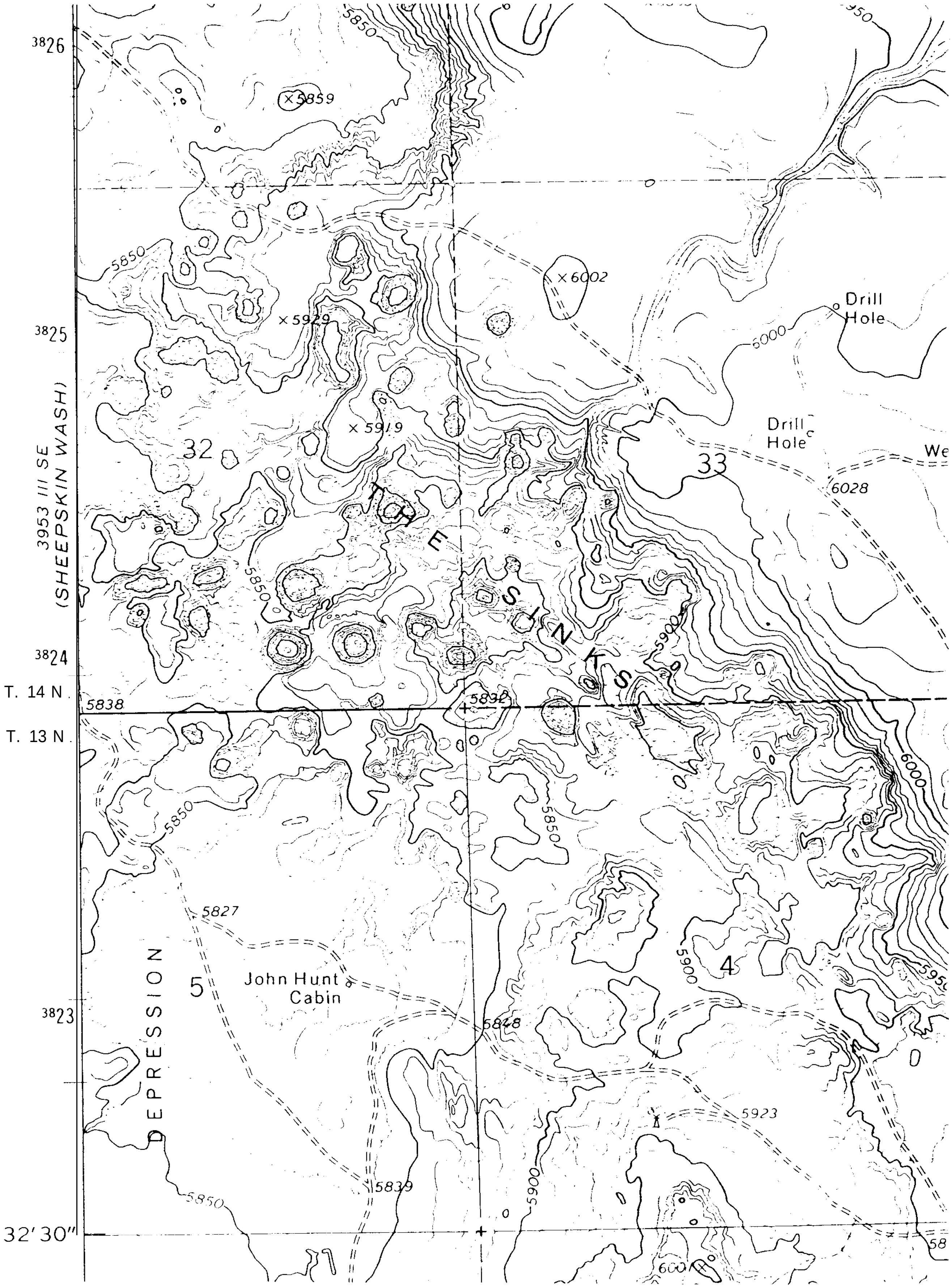


Figure 6 "The Sinks," 20 miles south of Holbrook and 6 miles west of Snowflake, AZ, adjacent to the large subsidence / collapse zone along the south margin of the Upper Supai halite dissolution front. Large fissures and numerous sinkholes up to 150 ft deep are currently active; the trend is parallel to the Holbrook Anticline and the dissolution front. Scale: 1"= -1400 ft.

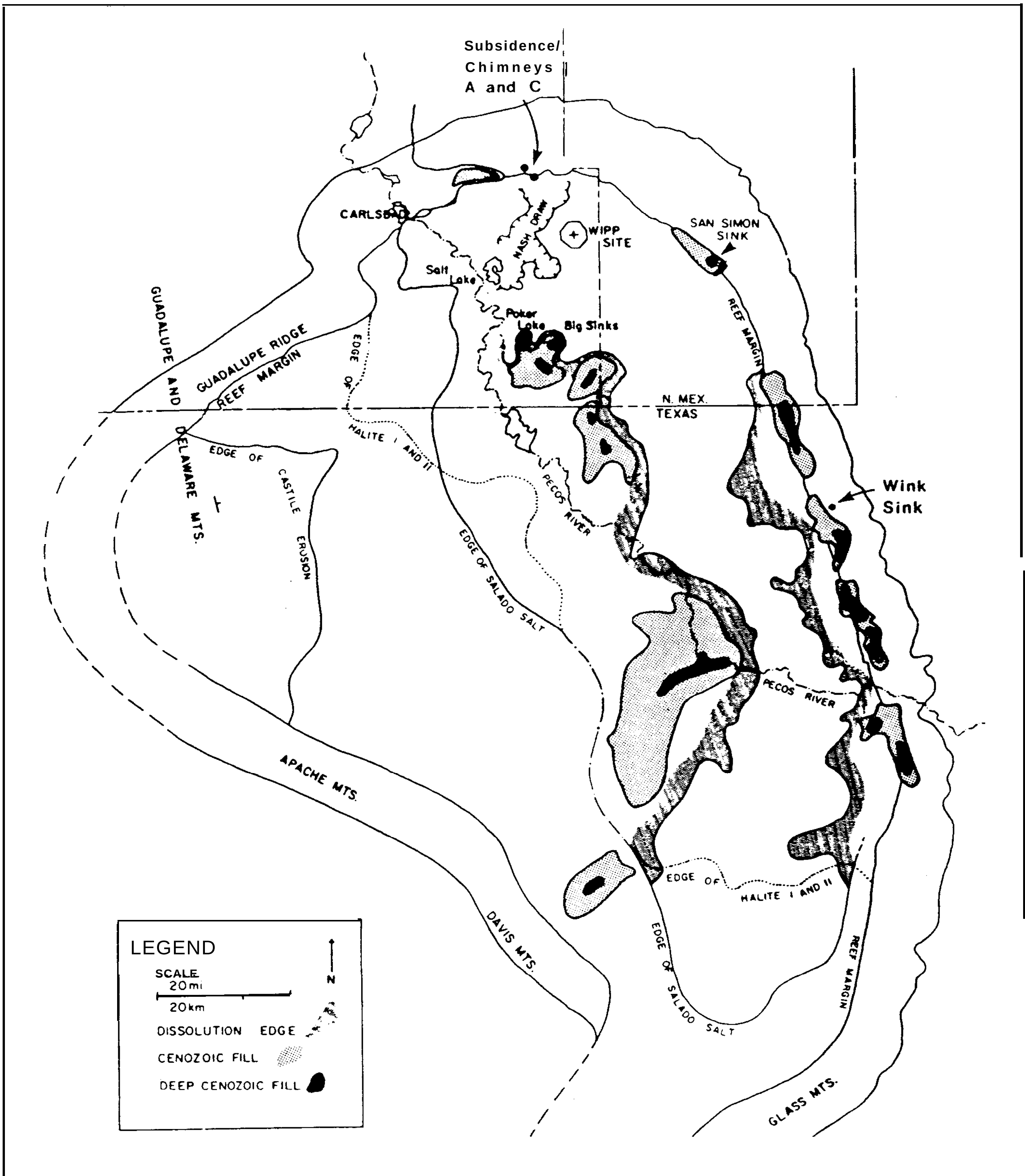


Figure 7 Delaware Basin, southcast New Mexico and West Texas, showing location of dissolution / subsidence features around the evaporite margins, and especially the Capitan Reef, with its more porous and fractured limestone. From Davies, 1983, Fig. 1-9.